Calibration Data, and Their Use in Analysis GSFC X-Ray Astronomy School

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Abstract

I will describe in very general terms how flux incident on an X-Ray telescope observatory is transformed into the detected signal via the response of the instruments, and then describe the specific kinds of calibration files we derive from the response for use in data analysis. This will include terms from the telescope mirrors, diffraction gratings, and detectors, as well as their geometric configuration and relative motions. The type of calibration objects required depends to some degree upon the type of analysis to be done (broadly: imaging, spectral, and temporal), and upon the data quality. Inferences about physical source properties are ultimately, and intimately, tied to the quality and form of calibration data.

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Fundamental Response Equation

$$\underbrace{C_D(\sigma,h,t)}_{\text{Counts}} = \underbrace{T(\sigma,t)}_{\text{Good Time}} \int d\lambda \int d\hat{p}\, \underbrace{R(\sigma,h,\lambda,\mathcal{R}(t)\cdot\hat{p},t)}_{\text{Response}}\ \underbrace{S(\lambda,\hat{p})}_{\text{Truth}}$$

[Counts] [s] [$\mathrm{cm^2\,counts\,photon^{-1}}$] [$\mathrm{phot\,cm^{-2}s^{-1}\text{Å}^{-1}}$]

σ = Detected position

h = Detected "wavelength"

t = Time

λ = Incident wavelength

$\hat{p}$ = Incident angle

Response is comprised of:

- Mirror area
- Mirror point-spread-function (PSF)
- Grating efficiency
- Grating line-spread-function (LSF)
- Detector efficiency
- Detector redistribution function (RMF)
- Time-dependent coordinate transformations ($\mathcal{R}\cdot\hat{p}$)

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The 3 Most Important Things are —

1. Calibration,

2.

3.

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The 3 Most Important Things are —

1. Calibration,
2. **Calibration,**
3. *Calibration!*

(The rest is "just" software, organization, and analysis.)

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Stages of Data Products

Telemetry —

Very raw

(voltages, frames, encoder counts)

Physical —

scaled, aspect corrected

(RA,Dec.; PHA; PI; Energy)

Filtered —

good detections, good aspect

("threshold" calibrations)

Source dependent —

Transmission grating

(wavelengths, diffraction angles)

Statistical filters

(cosmic rays, detector artifacts, vs. source photons)

Count-rate dependent corrections

(dead-time, pileup)

Binned —

images, spectra, light curves

(requiring customized binned responses)

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Analysis Preparation

Check your data —

Were "automatic" calibrations accurate?

View sky and detector coordinate images;

Examine PHA vs. time; Examine aspect, Good Time Intervals (GTI); . . .

Check calibration files —

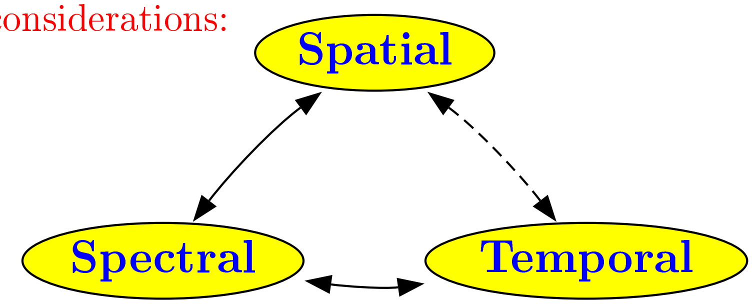
Know your Calibration Database! (CALDB)

Version, date, revision; do they match data products? Is re-processing needed?

Prepare Binned Observations —

What type of analysis is to be done?

Primary considerations:



Secondary considerations:

Spectral resolution;

Spatial resolution;

Source extent;

Temporal resolution;

Signal quality.

$\Longrightarrow$ Types of **RESPONSES** required

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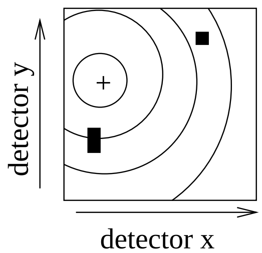
Spatial Response: EXPOSURE MAP

The *Exposure Map* retains spatial information at the expense of spectral.

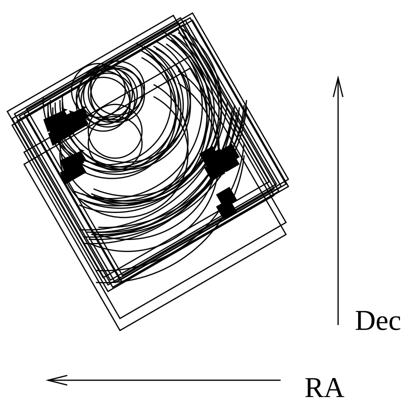
$$\int d\lambda\, S(\lambda, \hat{p}) \approx \frac{C(\Delta h, \hat{p})}{E(\Delta h, \lambda, \hat{p})}$$

Instrument Map — efficiency calibration information, band integrated.



$=$ mirror area $\times$ detector QE

Exposure Map — applies telescope aspect history and coordinate transformations ($=$ area $\times$ time).



$=$ Instmap $\otimes$ Aspect

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Spectral Response, Low Resolution

The spectral response retains spectral information at the expense of spatial.

$$C_\Omega(h) = \tau_{\mathrm{eff}} \int d\lambda\, D_R(h,\lambda)\, A_\Omega(\lambda,\hat{q})\, S(\lambda)$$

for a point source at location $\hat{q}$ for region Ω.

$D_R(h,\lambda)$ = Redistribution Matrix Function (or File), also known as the *RMF*; a probability.

$A_\Omega(\lambda,\hat{q})$ = Auxiliary Response Function (or File), also known as the *ARF*; an area times efficiency, or *effective area*. This includes the detector quantum efficiency and mirror area.

τ_{eff} = effective exposure time.

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Spectral Response, Dispersive

- Spatial & spectral information is tightly coupled;
- Imaging spectral ("PHA") & spatial information are tightly coupled.

$$C^m_{\Omega_i}(h) = \tau_{\text{eff}} \int d\lambda \, G^m_{\Omega_i}(\lambda, \hat{q}) \, A_m(h, \lambda) \, S(\lambda)$$

$G^m_{\Omega_i}(\lambda, \hat{q})$ = Grating RMF, diffraction order m, which describes the line-spread-function (LSF) (a redistribution from λ into spatial bin Ω_i)

$A_m(h, \lambda)$ = Grating ARF, for order m. This includes grating efficiencies as well as the mirror's and detector's.

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Response, Temporal

— spectrum, source counts, or image vs time bin.

Need exposure map or ARF vs time, or assurance that the mean is appropriate. If necessary, integrate:

$$C(\Delta h, \Delta t) = \int dt \int dh\, C(h,t) = \ldots$$

Response, Spatial PSF

— The PSF is a complicated redistribution (especially for X-ray optics!). The ARF must include the PSF fraction appropriate to the ARF region and source position.

— The PSF is generally a function of energy and source position relative to the optical axis (two vectors): $PSF \rightarrow PSF(\lambda, \hat{p}, \hat{q})$.

The PSF is often treated empirically (via a library of observed or ray-traced images), and is not formalized as a "response" function.

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Practical Applications in Data Analysis

Much analysis can be done with the three basic response functions:

ARF (spectral response, or effective area; low or high resolution)

RMF (spectral redistribution; low or high resolution)

Exposure Map (imaging mode)

But some cannot, such as ray-trace simulations or extended source analysis.

Forward-folding —

– Guess model parameters

– Predict observed signal (counts vs channel, or position)

– Repeat, until you minimize residuals.

E.g., `XSPEC` spectral fitting;

Or, source spatial model times exposure map.

"Inversion" —

– Division of counts image by exposure map;

– Division of high-resolution spectrum by ARF;

WARNING: inversion can be dangerous! Ignoring source-model dependence in maps or redistribution in spectra can lead to inaccurate fluxes.

Simulation –

Ray-trace simulations necessarily use calibration data at the lowest, most detailed level. For instance,

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rays require 3D geometry, and realistic offsets between filters and detectors. Analysis does not, since the signal can usually be defined adequately by the product of efficiencies.

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Issues Related to Calibration Data

Signal-to-Noise ratio —

The S/N can affect what calibration is appropriate for a given goal. For example, perhaps the signal is not large enough to warrant spectral fitting, and exposure map "inversion" is adequate for a survey of faint sources.

Computation speed —

On the other hand, perhaps the above survey is large, and computation of ARFs is much faster (after which you can still "invert" by dividing the integrated ARF by the total counts).

Calibration Quality —

Calibration is not perfect! However, little analysis takes the uncertainty of the calibration into account. This is indeed difficult because it is typically a systematic term (e.g., 3%). With high-signal data, the systematic can dominate residuals.

Furthermore, there are always regimes where calibration is poor (10%, 20%, or more).

Don't over interpret data without considering calibration quality!

Note: systematics cannot be "added in quadrature" to statistical uncertainties. Responses typically have some rigidity to the function (i.e., 10% means over some correlation distance within which the function can only be perturbed in a smooth fashion).

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Add data, or fit jointly? –

It may be tempting to add spectra or images, and also add the responses, in order to have fewer objects to analyze, and to improve counting statistics. However, you may compromise knowledge of systematics or calibration quality dependent on spatial or spectral region. (e.g., you can't as easily ignore the bad parts in favor of the good.)

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Further Reading

http://space.mit.edu/%7Edavis/rsp2001.html

"The Formal Underpinnings of the Response Functions used in X-Ray Spectral Analysis", Davis, J.E., 2001, ApJ, 548, 1010.

This paper gives a rigorous mathematical derivation of the ARF, RMF, and exposure map for imaging and grating modes.

http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_intro.html

Basic definitions and descriptions of the High Energy Astrophysics Science Archive Research Center calibration database.

http://cxc.harvard.edu/caldb/about_CALDB/intro.html

"Describes the purpose of the CALDB, gives HEASARC references, and presents the directory structure. Useful if you want to know about the CALDB itself, who to talk to about it, and how it actually works. This section also provides a walking tour of the Chandra CALDB web site."

http://space.mit.edu/CXC/docs/expmap_intro.ps.gz

"Introduction to Exposure Maps", in which examples are given of the accuracy of determining flux by ratios of counts with exposure maps.

http://space.mit.edu/%7Edavis/adass1999.html

"A Framework for the Development of Multi-Mission Software", John E. Davis, 1999, Astronomical Data Analysis Software and Systems IX, eds. N. Manset, C. Veillet, and D. Crabtree.

This paper discusses treatment of instrument responses as generic functions by encapsulation of mission-dependent calibration files.

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